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## **Calculated Thermal Response of High-Power Switch to Short Pulses**

**by Gregory K. Ovrebo**

**ARL-MR-0853**

**October 2013**

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) October 2013	2. REPORT TYPE Final	3. DATES COVERED (From - To) October 2012–March 2013			
4. TITLE AND SUBTITLE Calculated Thermal Response of High-Power Switch to Short Pulses			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Gregory K. Ovrebo			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-SED-P 2800 Powder Mill Road Adelphi, MD 20783-1197			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-MR-0853		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The U.S. Army Research Laboratory (ARL) has calculated the thermal response of a solid-state switch module to very short high-current, high-power pulses. A simplified model of the module was used in finite element simulations of heating in the eight silicon (Si) Super Gate Turn-Off Thyristors (SGTOs) in the module. Simulations calculated the temperatures of the devices in response to a series of pulses tens of microseconds ( $\mu$ s) wide in a span of 4 or 5 seconds (s). We calculated that the switch module could absorb several pulses in a brief period without increasing the temperatures to damaging levels.					
15. SUBJECT TERMS simulation, pulse power, silicon					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 20	19a. NAME OF RESPONSIBLE PERSON Gregory K. Ovrebo
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	19b. TELEPHONE NUMBER (Include area code) (301) 394-0814		

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## 1. Introduction

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The U.S. Army Research Laboratory (ARL) has evaluated semiconductor switch modules composed of Super Gate Turn-Off Thyristors (SGTOs) designed and fabricated by Silicon Power Corporation (SPCO). The switches are intended to handle kiloamp-level currents and may dissipate peak powers measured in megawatts. Recent experiments measured the response of a switch module composed of eight SGTOs to single short, high-current pulses. We performed simulations of those experiments to calculate the temperature changes that occur inside the devices, where measurement is not possible. We also simulated worst-case operating conditions in which the switches handle several pulses within the space of 4 or 5 seconds (s).

Modeling and simulation were performed with SolidWorks\* 3D modeling software and SolidWorks Simulation computational fluid dynamics software from Dassault Systèmes.

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## 2. Switch Module Model

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The original switch model is shown in figure 1. It includes a module composed of eight SGTO die, lugs and spacers, and base, as well as an aluminum coldplate to conduct heat from the module. This model would require a very fine mesh to properly convey the level of detail shown in this figure; a finer mesh requires more calculation time and more computer memory.

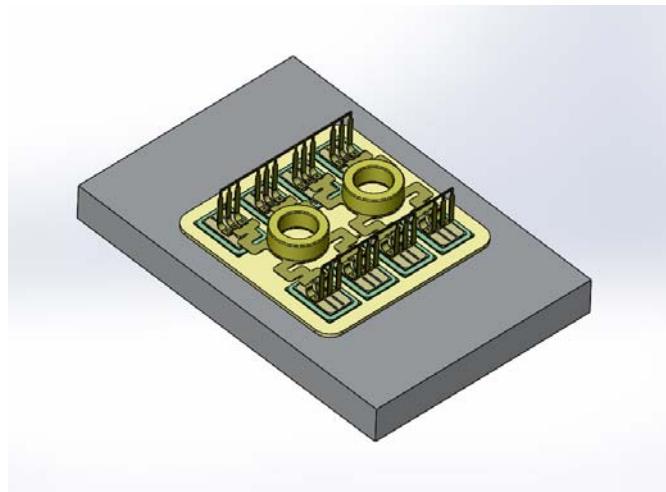


Figure 1. Original model of the solid-state switch with SPCO SGTOs.

In order to reduce the computation time spent in our thermal simulations, we simplified the original model, reducing the curves and fillets to a geometry suitable to a rectangular mesh,

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\* SolidWorks is a registered trademark of Dassault Systèmes SolidWorks Corporation.

while attempting to preserve the dimensions and volume of the parts (and materials) for our time-dependent thermal calculations. Figure 2a shows the simplified model.

We further simplified the model, and reduced simulation run times, by taking advantage of the symmetry of the model and using one-quarter of the simplified model for simulation. Note that in figure 2b we have also eliminated the spacers from the model; they have no significant influence on the thermal response of the switch in the timespans studied.

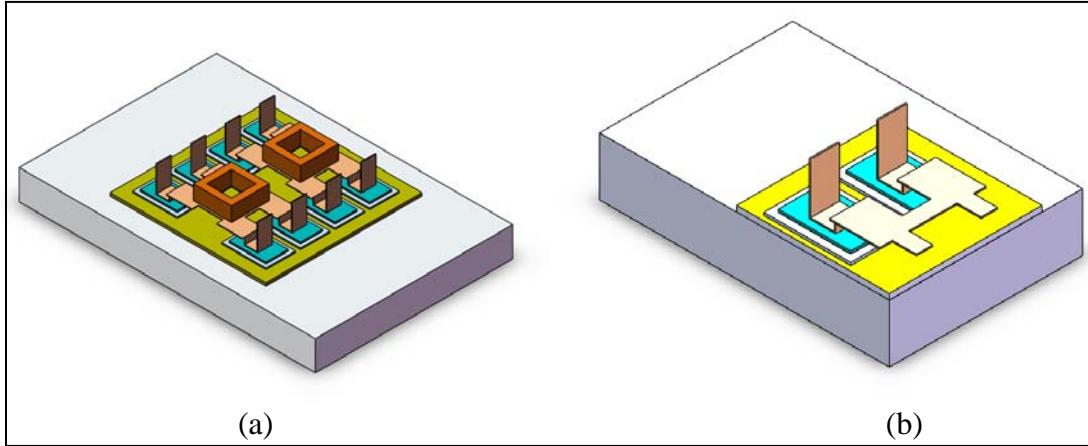


Figure 2. Simplified SGTO switch models: (a) full model, (b) quarter model.

Figure 3 shows part of the mesh, composed of rectangular elements, used in our thermal simulations of the SGTO switch.

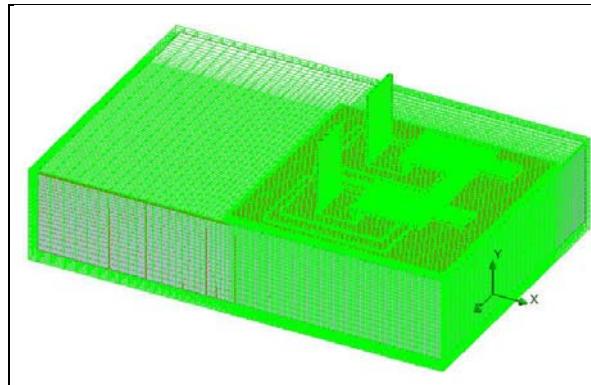


Figure 3. Mesh of the one-quarter model of the solid-state switch and coldplate.

### 3. Thermal Simulations

The initial temperature of the model and of the air surrounding it was defined to be 70 °C. The bottom surface of the coldplate on the switch module was also defined to be 70 °C; this served as

a sink for heat generated in the SGTOs. The top surface of the circuit board was subject to natural convection, which we included in our simulation by defining those surfaces to have a convection coefficient of  $10 \text{ W/m}^2\text{-K}$ .

The time-dependent thermal inputs for our simulations were derived from measurements of voltage drops and current in the SGTOs made during experimental characterizations performed with the solid-state switch modules. Curves of power versus time were culled from much larger files of data recorded at 0.1-microsecond ( $\mu\text{s}$ ) intervals. Figure 4 shows the narrower pulse, 35  $\mu\text{s}$  long, with a peak power of 1.7 MW per device. We assumed that the switch module distributes the power equally among the SGTOs. In our simulation, power was applied uniformly throughout the active part of the die, rather than applying it solely to a junction within the die.

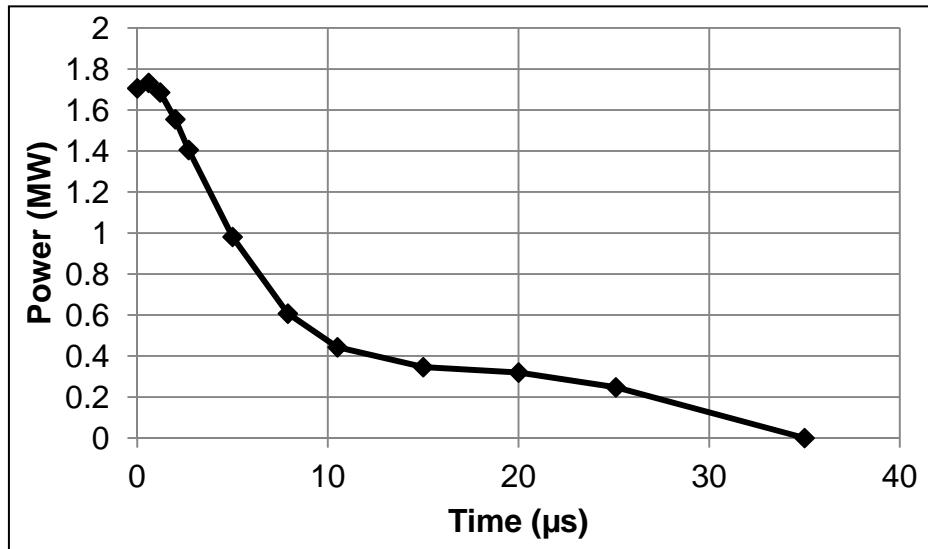


Figure 4. Time profile of power applied to each silicon (Si) SGTO die during a 35- $\mu\text{s}$  pulse.

Figure 5 plots the average temperature in the active part of the Si SGTO die as calculated during the 35- $\mu\text{s}$  pulse. The die temperature increases about 62 °C by the end of the pulse.

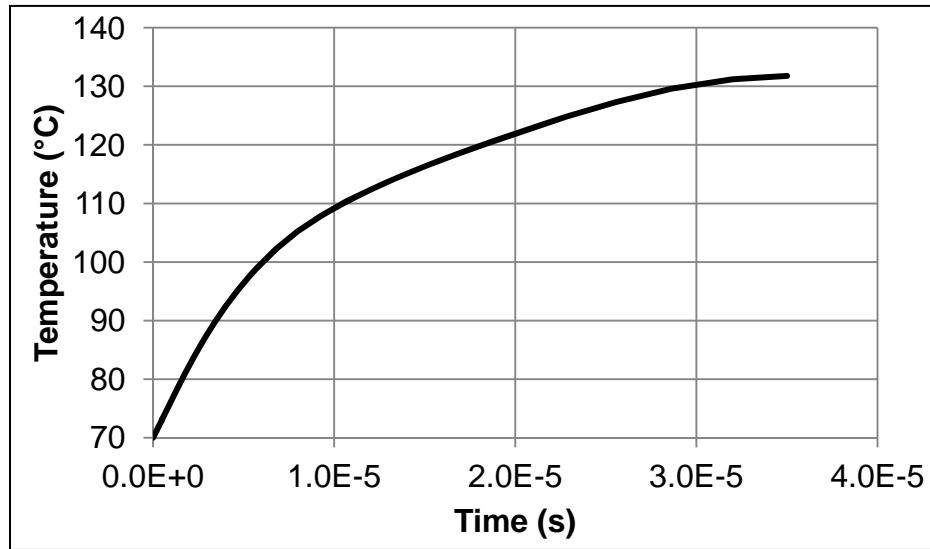


Figure 5. Average temperature in the active part of the SGTO die during a 35-μs pulse.

Figure 6 is a temperature contour plot of the module at the end of the single 35-μs pulse. While the active part of the die has reached a temperature in excess of 130 °C, that part of the die is covered with a lid, and the observable part of the module has reached a maximum temperature of about 100 °C. Little of the heat in the first pulse has been conducted outside the active die in 35 μs.

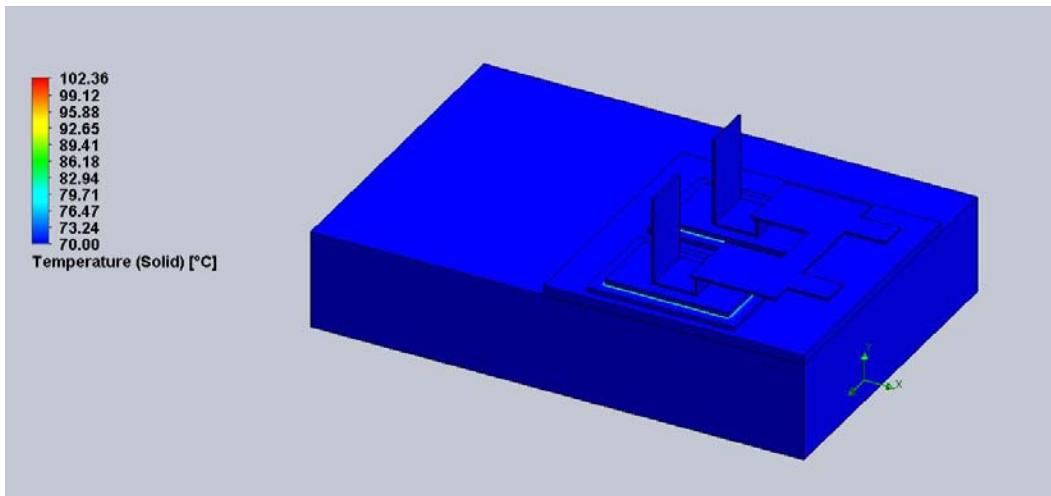


Figure 6. Temperature contour plot of the switch model at the end of a single 35-μs pulse.

Figure 7 shows the average temperature in the active part of the SGTO die during the pulse and the decline in temperature after the end of the pulse. The “off” time is 1.66 s, at the end of which the die has almost returned to its initial temperature of 70 °C.

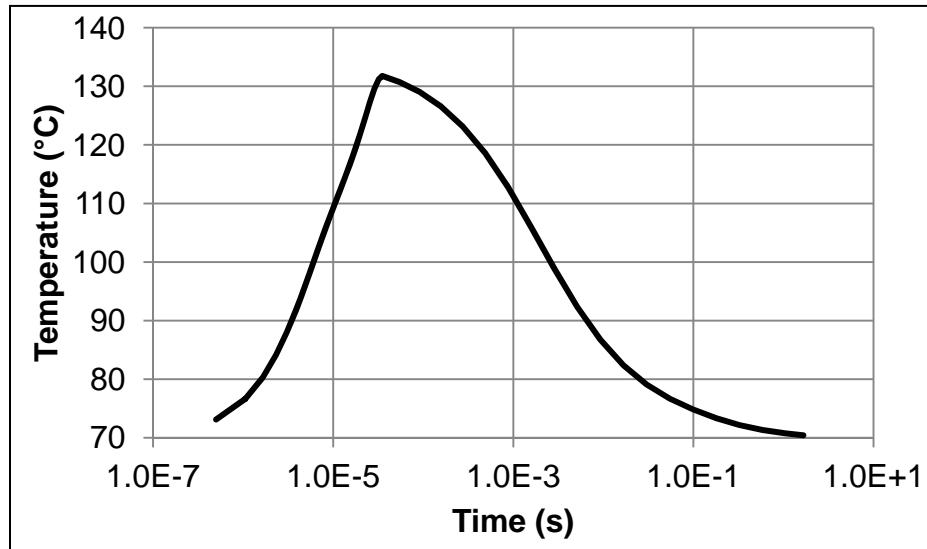


Figure 7. Average temperature in the SGTO die during a 35- $\mu$ s pulse and 1.66-s cooling period.

Next we calculated how the temperature of the SGTOs rose and fell during a series of pulses. We used two cases: the first was five 35- $\mu$ s pulses in a 4-s period, and the second was four 35- $\mu$ s pulses in a 5-s period. Our interest was in discovering whether or not the temperature of the devices stays within a safe operational range. Figure 8 shows the average temperature of the SGTOs during that 5-pulse train. We can see that SGTOs return almost to the original baseline temperature between pulses, and the average temperature rises with each pulse to just over 130 °C. Silicon devices may not operate as efficiently at such temperatures as they do at room temperature, but are not likely to be damaged by such short transits to high temperatures.

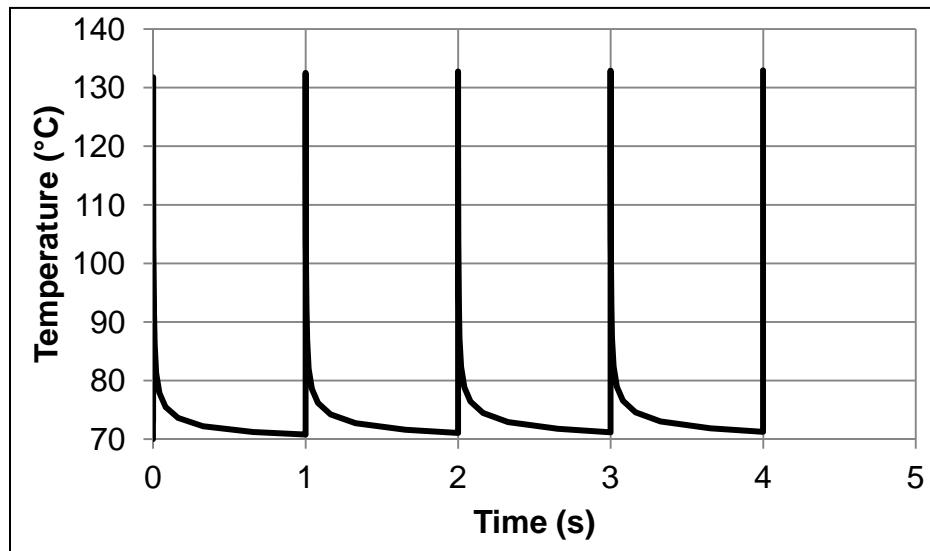


Figure 8. Average temperature in the SGTOs during a train of five 35- $\mu$ s pulses.

Figure 9 shows a temperature contour plot of the switch module at the peak of the last 35- $\mu$ s pulse. There still is little sign of heat spreading through the module after 5 s, and visible temperatures are within one degree of those at the peak of the first pulse.

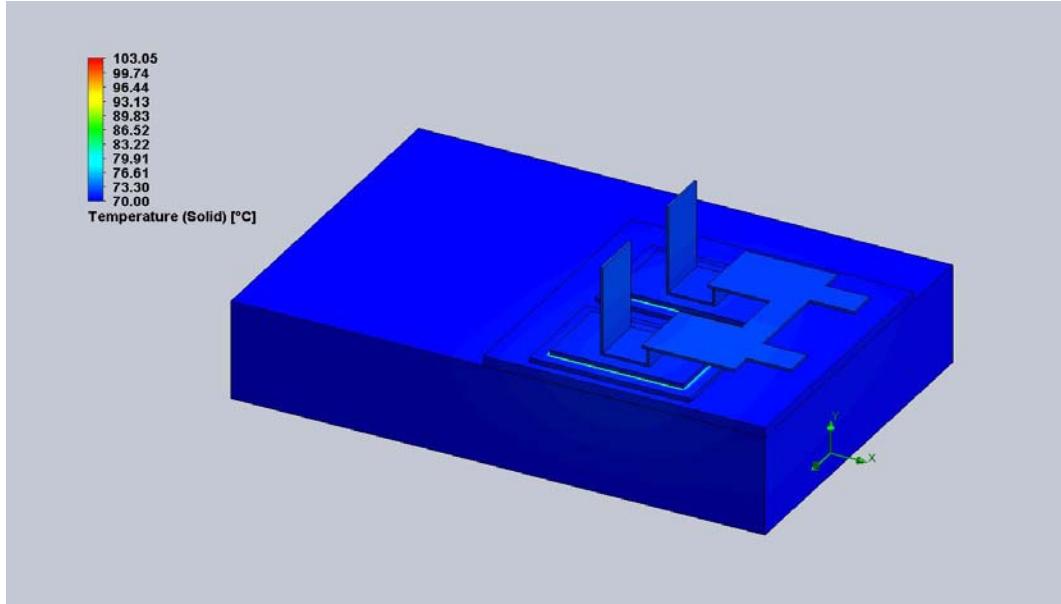


Figure 9. Temperatures on the switch module at the peak of the fifth pulse.

Figure 10 shows the calculated average temperature in the less stressful case of four pulses in 5 s. The results are consistent with the previous case, with the average temperature returning to initial levels between pulses.

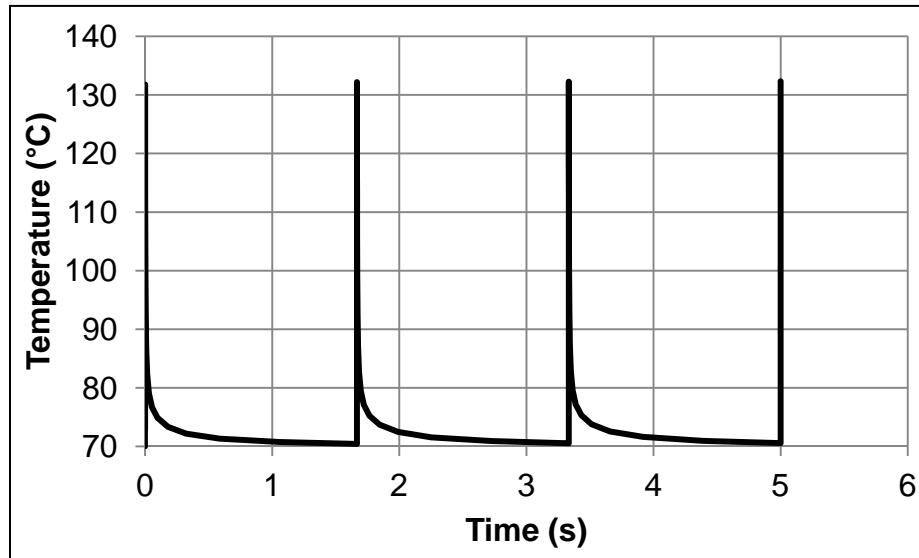


Figure 10. Average temperature in the SGTOs during a train of four 35- $\mu$ s pulses.

Our second set of calculations used a 54- $\mu$ s-wide pulse as a thermal input to the SGTO switch model. Figure 11 shows a plot of power dissipated in each SGTO, derived as before from a much larger data set of voltage and current measurements made at ARL. Peak power is 1.5 MW per SGTO, assuming equal distribution of power among the SGTOs in the module.

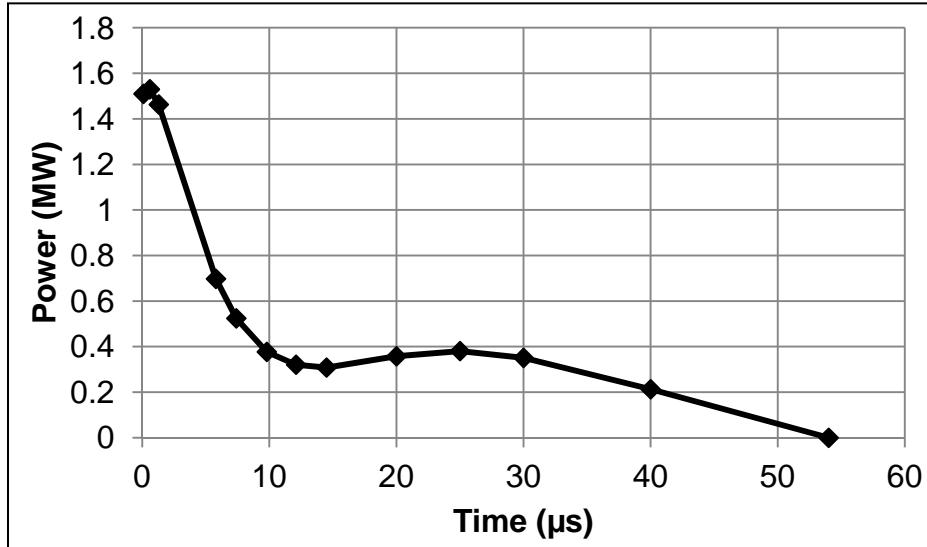


Figure 11. Time profile of power applied to each Si SGTO die during a 54- $\mu$ s pulse.

As with the 35- $\mu$ s pulse case, we calculated the thermal effects of a single pulse, a series of five pulses in 4 s, and four pulses in 5 s. The effects of a single pulse are shown in figures 12, 13, and 14. The longer pulse raises the device temperature over 140 °C, about 10 °C higher than the 35- $\mu$ s pulse.

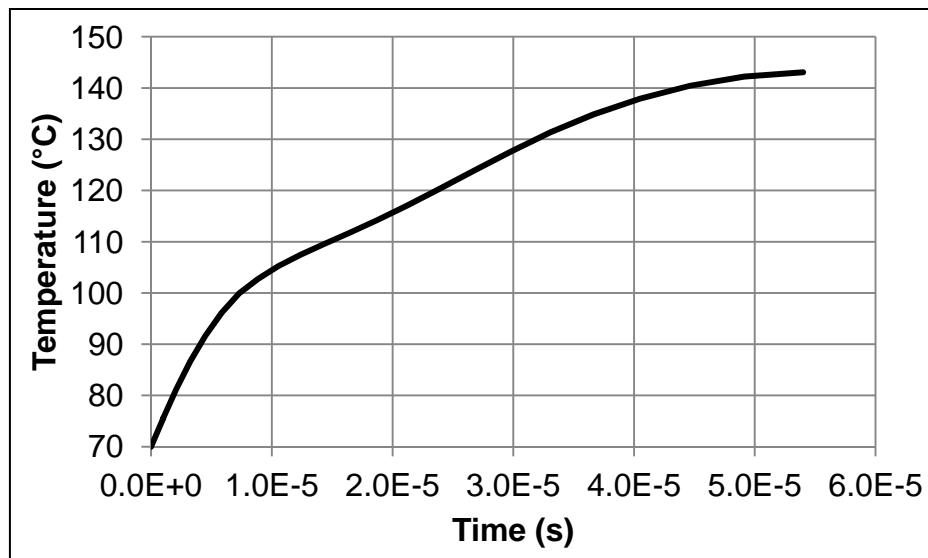


Figure 12. Average temperature in the active part of the SGTO die during a 54- $\mu$ s pulse.

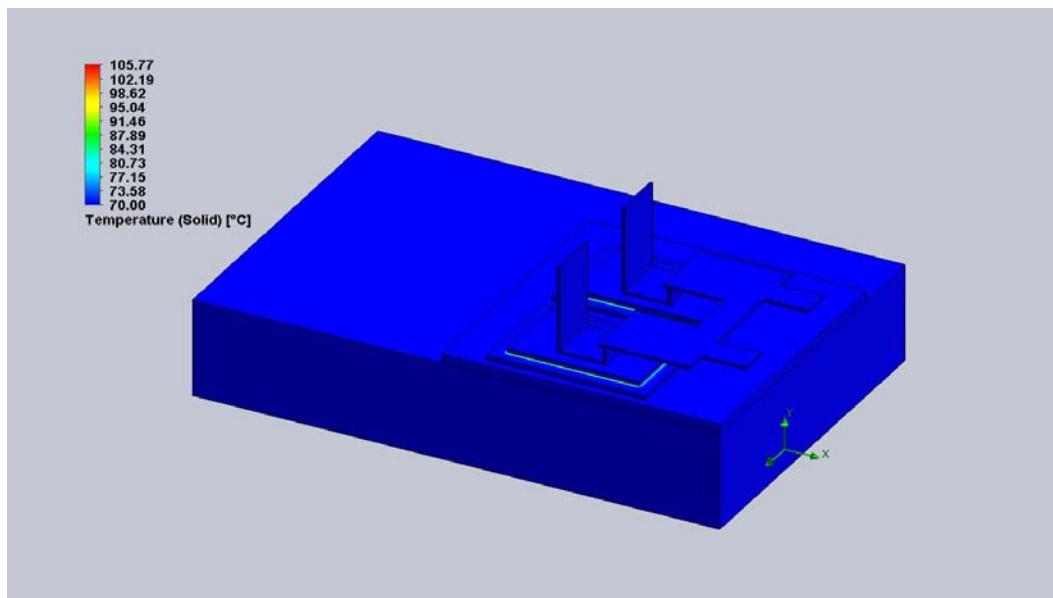


Figure 13. Temperature contour plot of the switch model at the end of a single 54- $\mu$ s pulse.

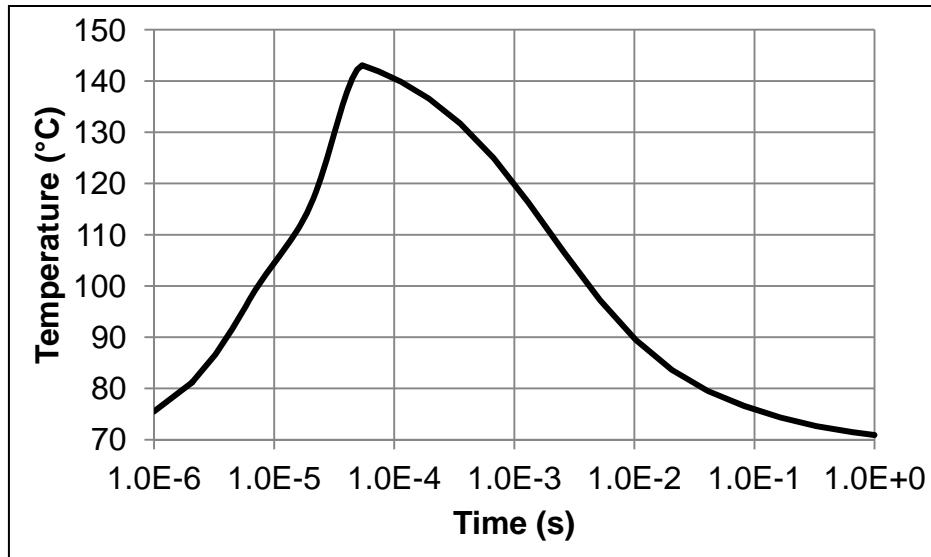


Figure 14. Average temperature in the SGTO die during a 54- $\mu$ s pulse and 1-s cooling period.

We calculated the effects of 4- and 5-pulse trains with the 54- $\mu$ s pulse. Figure 15 plots the average temperature of the SGTO die during a series of five pulses in 4 s. Figure 16 is a contour plot of temperatures on the switch module at the peak of the fifth 54- $\mu$ s pulse, which should demonstrate worst-case thermal effects. Figure 17 plots the average temperature of the SGTO die during a series of four pulses in 5 s.

As each pulse was applied, the average temperature in the active part of the SGTOs rose to more than 140 °C, and returned almost to the baseline temperature between pulses. The SGTO temperature at the end of the last pulse in both cases was approximately 144 °C.

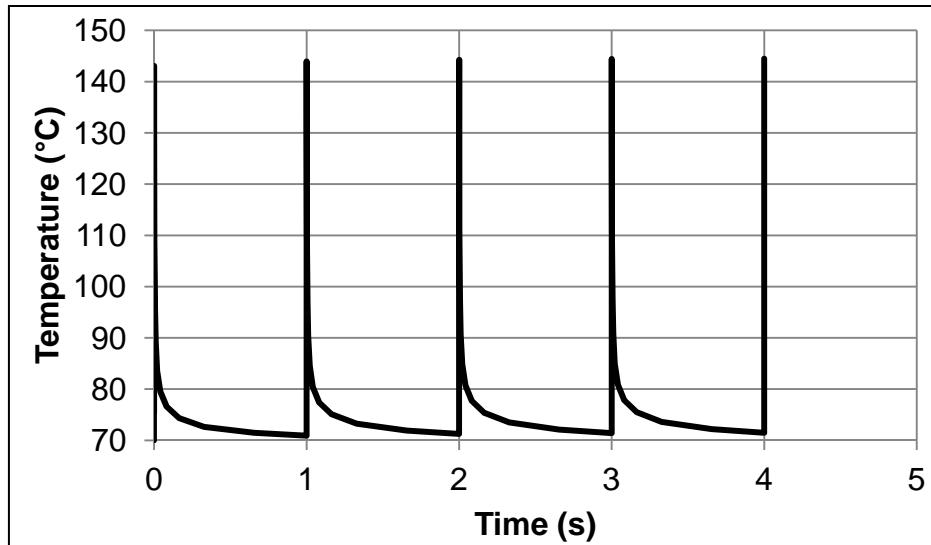


Figure 15. Average temperature in the SGTOs during a train of five 54- $\mu$ s pulses.

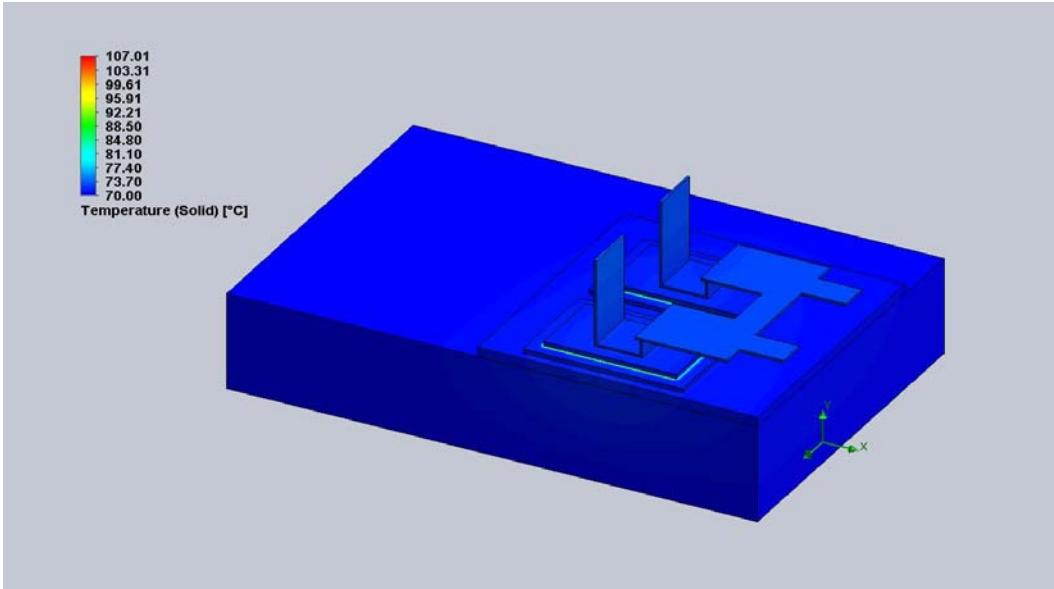


Figure 16. Temperature distribution in the SGTO module at the peak of the last of five 54- $\mu$ s pulses.

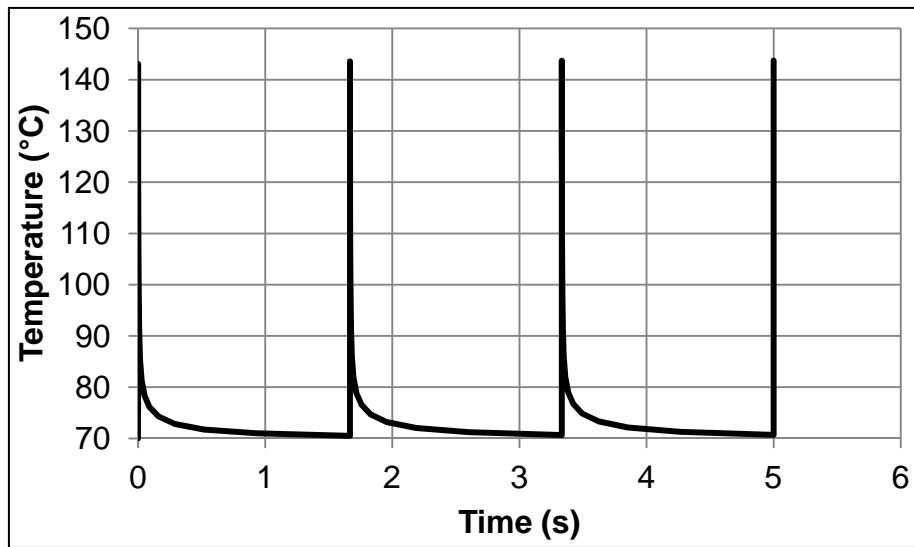


Figure 17. Average temperature in the SGTOs during a train of four 54- $\mu$ s pulses.

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#### 4. Conclusions

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We have performed simulations of short pulses, 35- and 54- $\mu$ s-wide, with peak power exceeding 1.5 MW, into an Si SGTO switch module, reproducing the conditions of tests conducted at ARL's Power Conditioning branch. Our model shows a quick rise in the temperature of the SGTOs during the pulse, but peak temperatures are within safe operating limits for Si devices.

The heat in the devices dissipates quickly into the surrounding package and into the coldplate to which it is mounted. Heat conduction occurs rapidly enough that the devices' temperature returns very close to their initial temperature within about 1 s after the end of the pulse. Our calculations predict that the peak temperatures in the SGTOs will increase little over time when we apply a series of short pulses over 4 or 5 s. This indicates that our switches should be able to withstand repeated cycling at high power levels without sustaining heat-related damage or suffering serious degradation of performance.

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## **List of Symbols, Abbreviations, and Acronyms**

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ARL      U.S. Army Research Laboratory

$\mu\text{s}$       microsecond

s      seconds

SGTO      Super Gate Turn-Off Thyristor

Si      silicon

SPCO      Silicon Power Corporation

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